

High Fidelity VSF Measurements and Inversion for RaDyO (Hi Fi RaDyO)

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LONG TERM GOALS

Time and space dependent radiance distributions at the sea surface are a function of the shape of the incident distribution on the surface, modification by the sea surface itself from topography and transmission characteristics, and alteration by the Inherent Optical Properties (IOPs) of the surface ocean. The long term goal of the proposed work is understanding this last controlling factor. With a knowledge of the IOPs, radiance fields can be directly computed from the incident field using the equation of radiative transfer, now embedded in commercially available code (e.g., Hydrolight).

With the state of current technology and methodologies, the primary obstacles in understanding subsurface IOPs and their high-frequency dynamics are a lack of 1) volume scattering instrumentation, 2) comprehensive inversion models linking the IOPs with the causative bubble, particulate, and dissolved matter in the water (which in many cases will require input dependent on 1), and 3) suitably stable, non-intrusive platforms to sample the subsurface ocean. The first two challenges are addressed in this project.

OBJECTIVE

There are two overarching objectives for this project:

- 1) To develop an in-situ volume scattering function device measuring volume scattering from 10° to 170° at 10° intervals and sampling rates of 1 s^{-1} or better to sample the VSF in near-surface waters; and
- 2) To develop and refine IOP inversion models to resolve particle field characteristics on small spatial (cm's) and temporal ($<1\text{ s}$) scales in near-surface waters.

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APPROACH

Our design for the VSF device is illustrated in **Figure 1**. The device is called MASCOT (Multi-Angle Scattering Optical Tool). The source beam is a 30 mW 658 nm laser diode expanded with a Gallilean 2X beam expander to an approximately 3 mm X 8 mm elliptical shape. A wedge depolarizer is used to provide the unpolarized light needed for VSF determinations. Seventeen independent silicon diode detectors spaced in a semicircle 10 cm around the sample volume measure volume scattering from 10° to 170° at 10° intervals. The total pathlength for all scattering measurements is 20 cm. Independent detectors allow resolution of the VSF without any moving parts and time-consuming scanning. Additionally, each detector can be optimized for its specific dynamic range. Detector field-of-views (FOVs) range from 0.8° to 5° for the different detectors, with the narrowest FOVs associated with the detectors measuring scattering in the forward direction. Using proprietary electronics, a 20 Hz sampling rate for all channels has been achieved while maintaining a worst case signal:noise of 300:1. Relatively fast sampling rates are important in resolving VSFs in the highly dynamic ocean subsurface.

Polarized VSFs have now been successfully collected with the addition of filter mount placed in front of the source beam. A linear polarizer is used to obtain scattering from a vertically and horizontally polarized source (in terms of the Mueller scattering matrix elements, $(S_{11}+S_{12})/2$ and $(S_{11}-S_{12})/2$ are measured, so that S_{11} and S_{12} may be derived). Adding polarized scattering increases the amount of information on particle characteristics we are collecting, and is expected to improve our ability to discriminate different particle types (both the number of subpopulations and the accuracy of individual determinations). The degree of linear polarization (S_{12}/S_{11}) is most dependent on the degree of sphericity, particle size, and refractive index composition.

MASCOT calibration parameters have been derived in solutions of microspherical beads and the particle standard Arizona Road Dust (AZRD; Powder Tech. Inc.). A reference detector may be used to account for any fluctuations in source intensity. Coincident measurements of beam attenuation are required to correct for light losses along the optical path of the scattering measurements (all pathlengths nominally ~ 20 cm). Algorithms have also been contemplated that would account for attenuation without a separate direct measurement. The design in **Fig. 1** is made as small as possible while accommodating all necessary hardware, a criterion established in part to minimize this effect. Two MASCOT prototypes have been developed for redundancy in case a problem with a component arises. Two systems allow concurrent testing of different sensor components and selective gain tuning to optimize for different environments.

For the inversion modeling, we extend the capabilities of existing models (Twardowski et al. 2001; Twardowski and Zaneveld, 2004) by incorporating input from new VSF measurements and by adding bubble particle populations (clean and coated) in the models. At a minimum, we expect the inversion model will give us component concentrations and size distributions, with the components being organic particles (living+detrital), minerals, and bubbles. We expect to co-deploy the MASCOT and the commercially available near-forward VSF device LISST (Sequoia Inc.) in order to capture the VSF with good resolution from ~ 0.1 degrees to 170 degrees.

RaDyO field deployments took place in collaboration with other RaDyO investigators off Scripps Pier in January 2008 and in Santa Barbara Channel in September 2008. A subsequent deployment off the Hawaii islands is planned for May 2009. For these efforts, we are deploying CTD + AC9 (+ ACS) + MASCOT + LISST + ECO sensors in a real-time vertical profiling system (**Fig. 2**). We have also integrated two additional sensors for these deployments: 1) a high sampling rate fish-eye lens radiometer currently being developed by Marlon Lewis and Scott McLean of Satlantic, and 2) a bubble acoustic resonator provided by Svein Vagle and David Farmer. For the Scripps Pier experiment, a mobile deployment platform was configured so that measurements may be made along the length of the pier, with the expectation that higher concentrations of bubbles will be observed nearing the surf zone. For subsequent field work in SBC and Hawaii, we are deploying our sensor package off the R/V Kilo Moana.

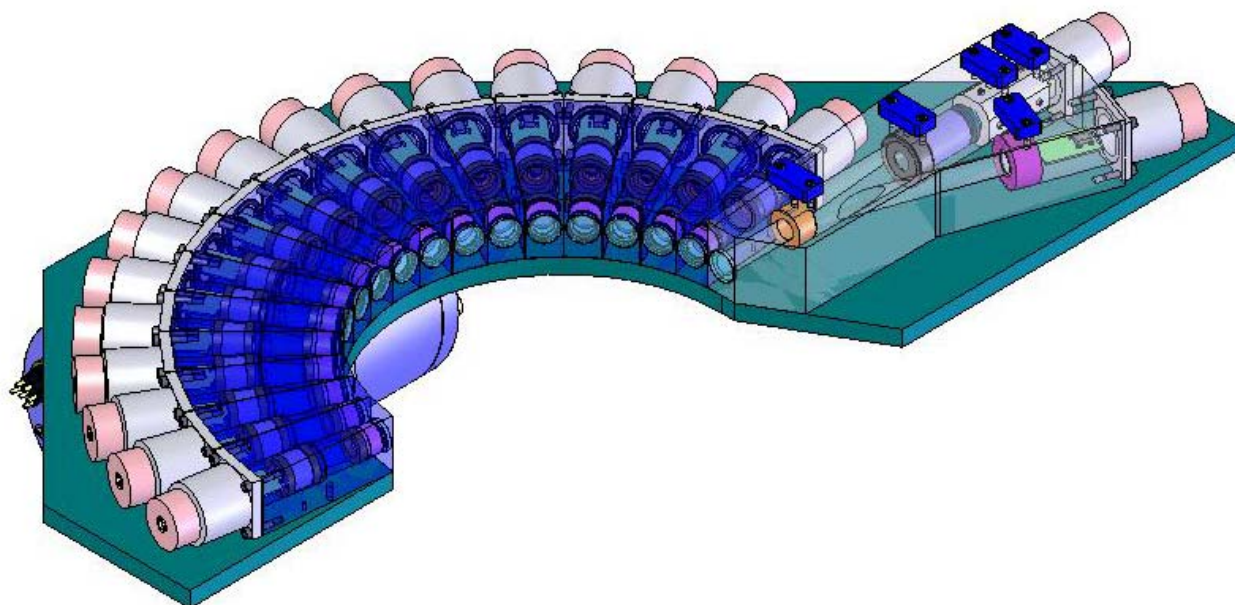


Figure 1. Oblique view illustration of the MASCOT. The VSF is resolved from 10 to 170 degrees in 10 degree intervals. Detectors are wedge shaped and arranged in a semi-circle on an aluminum frame to minimize reflections and perturbation of the water sample in the remote volume (center of semi-circle). The source assembly includes a 30 mW 650 nm laser diode, reference detector, beam expander, and wedge depolarizer. Wiring from all the detector modules and the source module feeds to a data handling unit.

WORK COMPLETED

- An IOP package including the MASCOT and LISST was deployed off Scripps Pier in January and in the Santa Barbara Channel in September during collaborative RADYO exercises;
- During the Scripps Pier and SBC deployments an acoustic bubble resonator (Vagle and Farmer) and a fish-eye lens camera (Lewis) were successfully integrated on the MASCOT IOP package;

- The MASCOT IOP package was also tested off the southern Californian coast in January, in the Southern Ocean in March, and in the New York bight in July in association with other funded work;
- A new calibration protocol was developed and implemented, correcting previous small bias errors in the VSF due to uncertainties in certain bead population parameters;
- A second MASCOT prototype with a larger dynamic range suitable for high turbidity environments (such as the surf zone) was constructed, tuned by our engineering group, and tested in the New York bight in July;
- Deconvolution of MASCOT VSFs collected off Scripps Pier into component VSFs associated with subpopulations of the bulk particle field has been successfully carried out using a least-squares minimization model based on Mie theory, including derivation of particle concentration and size distribution for each subpopulation.

RESULTS

Fig. 2 shows the MASCOT device in a custom cage with additional optical sensors ready for deployment. Measurement in the horizontal plane minimizes any shear perturbation of the sampled water parcel.

Fig. 3 shows our mobile deployment configuration off Scripps Pier in January. Typically, waves breaking shoreward of the sensor package's location produced suspended sediment and bubble plumes that became entrained in a seaward rip current running along the south side of the pier where the sensor package was suspended (**Fig. 4**). Bubble plumes had a visible expression for several seconds, while discrete suspended sediment plumes were clearly observed lasting for up to minutes. At high tide (the condition at the beginning of the **Fig. 4** time series), with the surf zone far shoreward of our position (>100 m), plumes with injected air bubbles typically did not persist long enough to reach our sensors, although episodic local breaking with localized bubble injection did occasionally occur. In these conditions, periodic plumes of suspended sediment entrained in the seaward rip current were clearly visible as turbidity maxima with a distinct VSF character (greater relative backscattering than the background). As the tide ebbed, the surf zone passed directly through our sampling region so that plumes of both bubbles and sediments were sampled. Plumes dominated with bubble particles exhibited a well-known enhancement in scattering at mid-angles, from 60 to 90 degrees (e.g., Zhang et al. 2004). This is the first time this mid-angle enhancement in scattering due bubbles has been observed in-situ. The 20 Hz sampling rate for all VSF channels allows excellent resolution of the bubble plumes as they rapidly evolve in time and space. A very low background scattering condition (particle attenuation less than 0.3 m^{-1} at 532 nm) enhanced our dynamic range in resolving intense scattering associated with episodic bubble and sediment plume generation.

The mid-angle enhancement in the VSF due to the contribution of bubbles can be clearly observed when VSFs are normalized to the background VSF. **Fig. 5** shows selected VSFs from the time series plotted in **Fig. 4** with this normalization. The strong mid-angle enhancement is evident.

A library of VSFs generated from a coated Mie theory model representing 5 particle subpopulations were fitted to measured VSFs using a least-squares minimization technique. This work has been carried out in collaboration with Xiaodong Zhang at the U. of N. Dakota. The 5 subpopulations were detrital material, minerals, diatoms, picoplankton, and bubbles. In this preliminary attempt, each is associated with size distribution and refractive index (np) parameters that we feel are generally appropriate from previously published results (**Table 1**). **Fig. 6** shows the modeled subpopulation VSFs for selected VSFs from the time series plotted in **Fig. 4**. Preliminary results are very encouraging and are consistent with anecdotal evidence (what we saw), sample composition as determined from particles collected on GF/F filters on-site, and with previous expectations for particle composition based on published optical-biogeochemical models (e.g., a high mineral content is expected based on the high relative amount of backscattering, Twardowski et al. 2001).

Table 1. Size distribution and refractive index parameters used to generate VSF libraries for the 5 particle subpopulations used in our preliminary model.

Subpopulation	Size distribution parameters	Refractive index
Detrital material (organic)	Junge-type distribution, Slope varying [3.2:0.2:5]	$1.03 + 0.0005i$
Minerals	Junge-type distribution, Slope varying [3.2:0.2:5]	$1.15 + 0.001i$
Diatoms	Log-normal distribution, modal size varying $10^{[0.6:0.1:1.4]}$ um, with 0.5um silicate shell	$1.05 + 0.001i$ core $1.10 + 0i$ shell
Picoplankton	Log-normal distribution, modal size varying $10^{[-0.7:0.1:0.3]}$ um	$1.05 + 0.001i$
Bubbles	Log-normal distribution, modal size varying [0.05:0.04:0.21 0.5 1 3 10] um, with 0.025um proteinaceous shell	0.75 core $1.20 + 0i$ shell

Fig. 7 shows the acoustics data collected with the Svein/Farmer bubble resonator concurrently with the MASCOT VSF data for the same **Fig. 4** time series. Excellent agreement between patterns in optical scattering from bubbles (positive displacements of the $\beta(60)/\beta(120)$ relationship relative to the background) and acoustic attenuation at multiple frequencies was observed. Decreases in $\beta(60)/\beta(120)$, particularly during the sediment turbidity plume maximum from 59-60 minutes (see **Fig. 4**), did not have any corresponding acoustic effect, demonstrating that the later turbidity maxima corresponding with positive displacements of $\beta(60)/\beta(120)$ were indeed related to bubble plumes. This is not only consistent with theoretical expectations but also visual observation at the time.

During the recent Santa Barbara Channel experiment, over 150 casts or time series were collected, including, for the first time, unpolarized scattering, scattering from a vertically polarized source, scattering from a horizontally polarized source, and dark offsets for all scattering instrumentation (including the LISST). Concurrently measured dark offsets ensures the highest degree of accuracy in our scattering results. Data from the first suite of vertical profiles collected with the MASCOT are shown in **Fig. 8**, including the VSF and the linear polarization ratio as a function of angle and depth.

Degree of linear polarization results were consistent with the relatively few previous laboratory based measurements by Voss and Fry (1984) and Quinby and Hunt (1988). Voss and Fry (1984) found that the peak in polarization was displaced to between 0.6 and 0.8 in samples from the Pacific and Atlantic Oceans. We observed a range of about 0.5 to 0.9 in this single cast. The polarization peak appears displaced to angles slightly greater than 90 degrees, also consistent with previously published works. This is the first time these measurements have been made in-situ. The addition of these polarization elements adds substantial new information on scattering that can be used to promote our long term objective of better understanding the community of particles with light scattering. We are in the process of adapting our current models to include the polarization results, which will expand our degrees of freedom in the fitting subpopulation VSFs 3-fold.

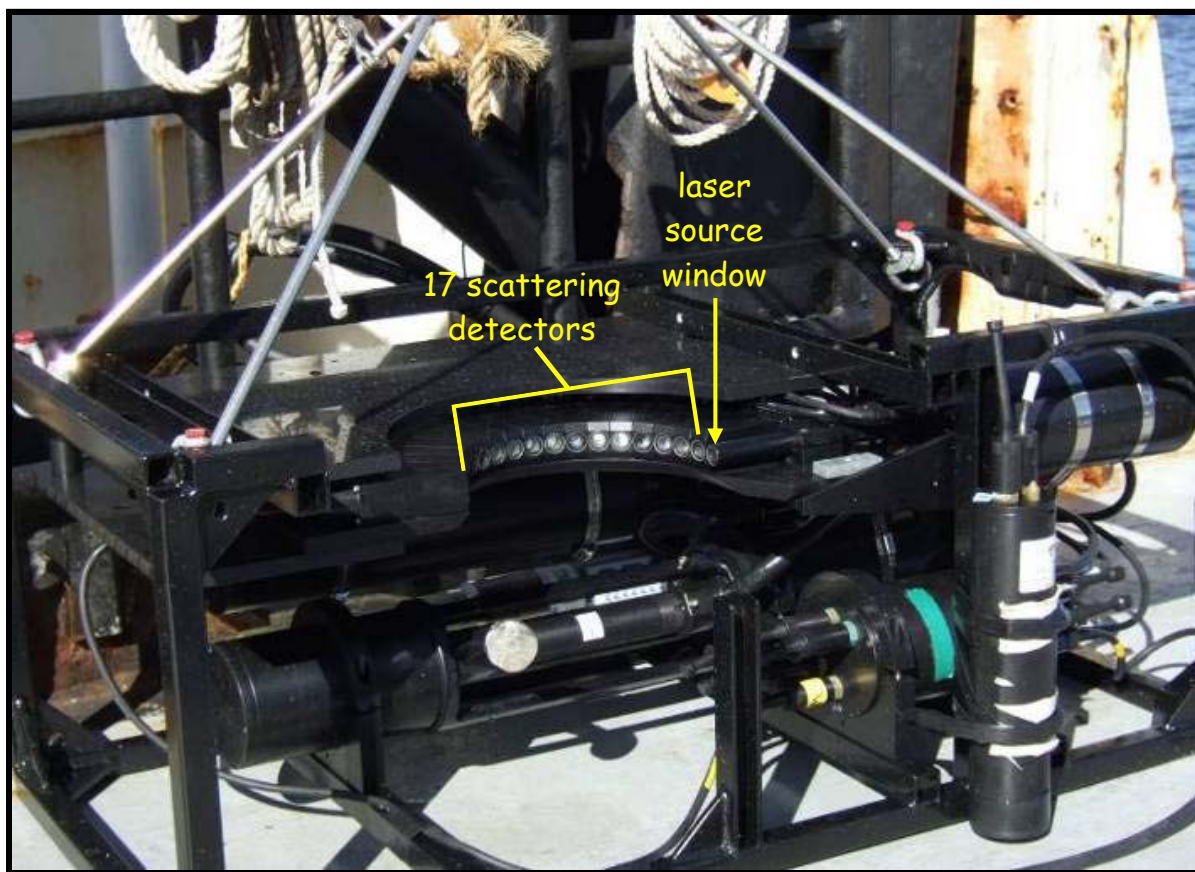


Figure 2. MASCOT VSF device mounted with other optical sensors in a custom cage designed to sample the subsurface domain.

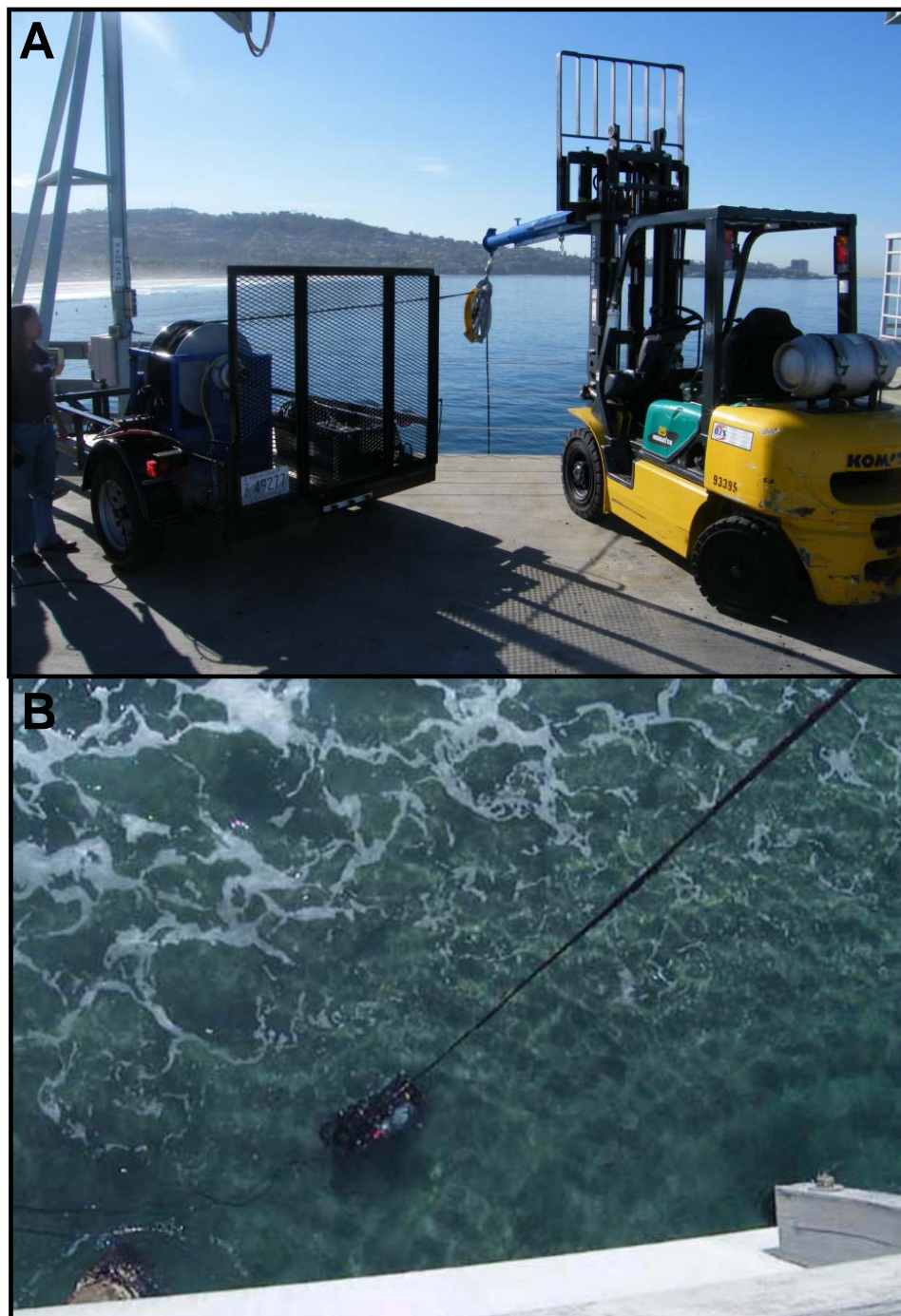


Figure 3. *An electric winch and forklift boom with mounted cable block were used as a mobile deployment platform for sampling with the MASCOT sensor package off Scripps Pier, January 2008 (A). Several time series were collected along the length of the pier both in and out of the surf zone (B). Episodic discrete plumes of sediment and bubbles could be observed flowing past the sensor package.*

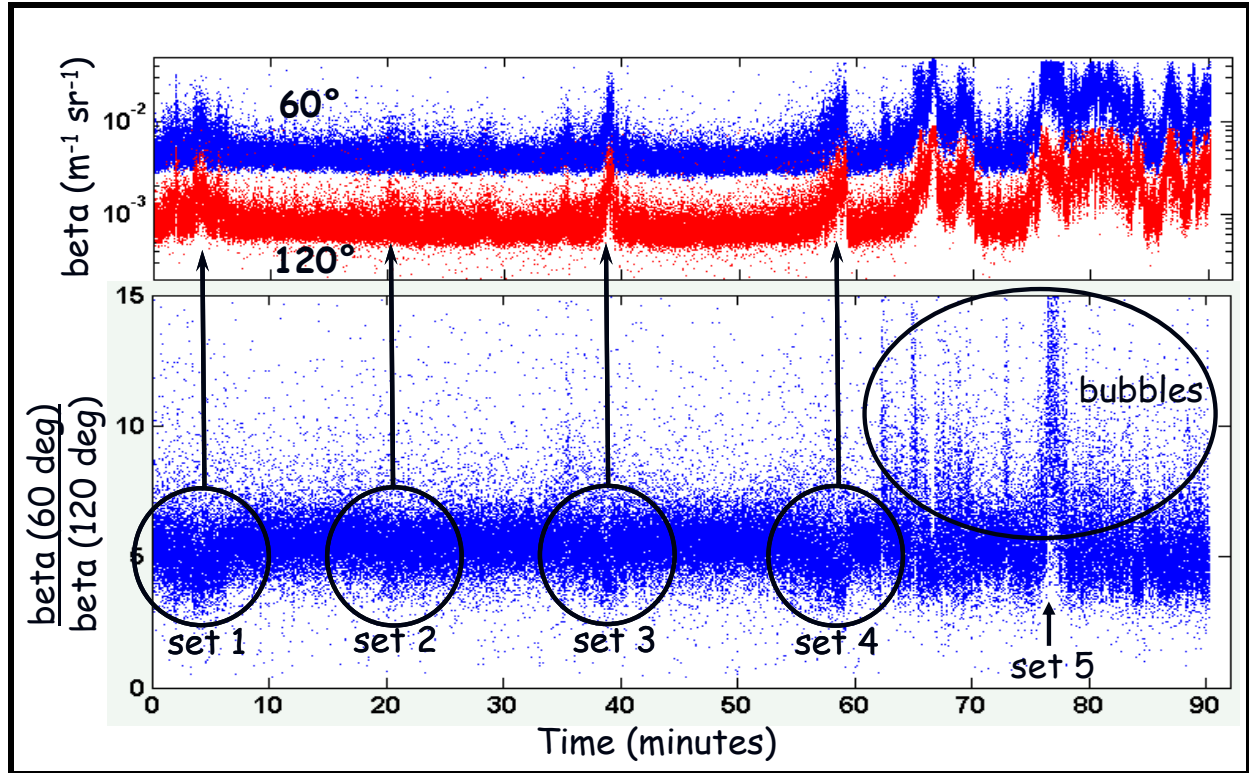


Figure 4. A 90 minute time series of the volume scattering function resolved at 60 and 120 degrees with the MASCOT off Scripps Pier. At the beginning of data collection the surf zone was shoreward of the sensor package and beginning to ebb. Breaking waves generated mixed bubble and sediment plumes which became entrained in a seaward rip current along the pier. By the time these plumes reached the sensor package (tens of seconds), the visible bubble influence had dissipated, leaving the strong sediment contribution. Maximum wave sets broke onshore every ~18 minutes. Scattering plumes from the first 4 sets were dominated by sediment, exhibiting a decreased $\beta(60)/\beta(120)$ relationship due to the sediment dominated plumes having a higher refractive index than the background particle population (e.g., Twardowski et al. 2001). Conversely, when the tide had sufficiently ebbed so that the surf zone was adjacent to the sensor package and active bubble plumes were being directly observed, scattering plumes exhibited an increased $\beta(60)/\beta(120)$ relationship due to the enhancement of mid-angle scattering due to bubbles (e.g., Zhang et al. 2004).

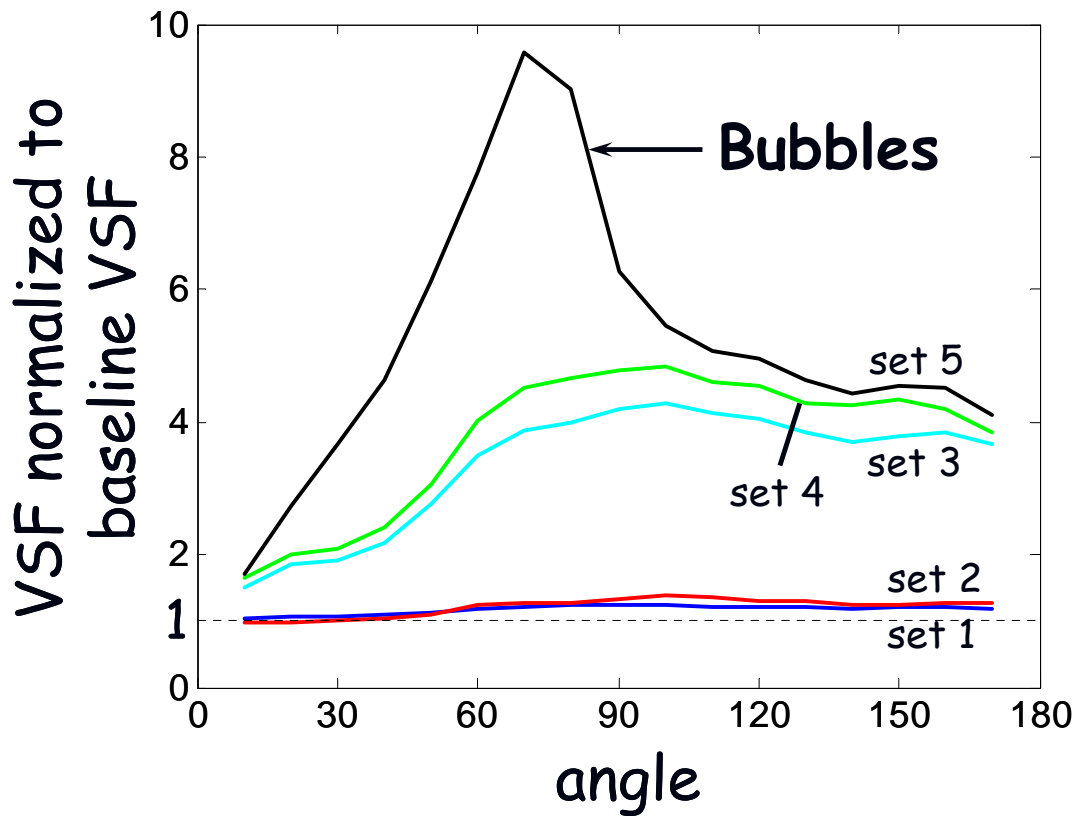


Figure 5. Volume scattering functions extracted from each of the 5 maximum wave sets labeled in Fig 4, normalized to the ambient background volume scattering function. The greater relative enhancement of scattering at angles greater than 60 degrees is clear for the first 4 wave sets, consistent with sediment dominated particle plumes. However, the plume associated with set 5 exhibited a marked enhancement in scattering in the middle angles between about 60 and 90 degrees, consistent with the scattering signature of bubbles.

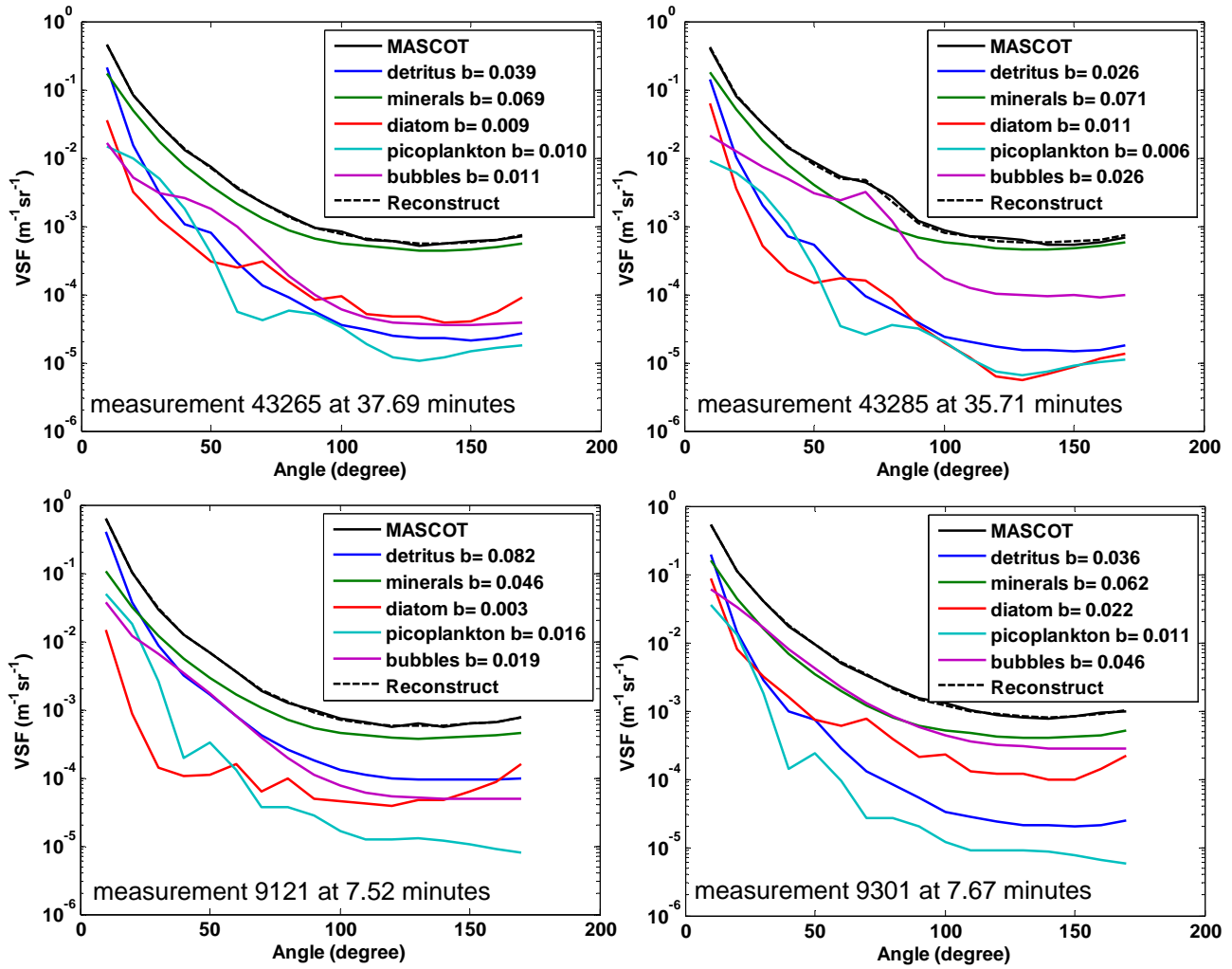


Figure 6. Subpopulation VSFs modeled using a least-squares minimization method. Four VSFs were chosen from the time series plotted in Fig. 4 (time of collection is indicated in each panel). The VSF at 37.69 minutes was collected during wave set 3 and exhibits a dominant contribution from suspended sediments, particularly at backward scattering angles. The VSF at 35.71 minutes was collected during passage of a locally generated “young” plume with a significant bubble influence (note mid-angle enhancement) in addition to the sediment contribution. The VSFs at 7.52 and 7.67 minutes were collected after the first wave set and demonstrate the type of variability in subpopulation contributions observed in the “background” between plume events associated with wave sets. In general, mineral sediments and bubbles appear to always be important, with the bubble contribution in these cases more indicative of the dominance of small bubbles (<10 μ m) that do not have the marked mid-angle enhancement. The b values in the legends correspond to the absolute contribution to total scattering for each subpopulation.

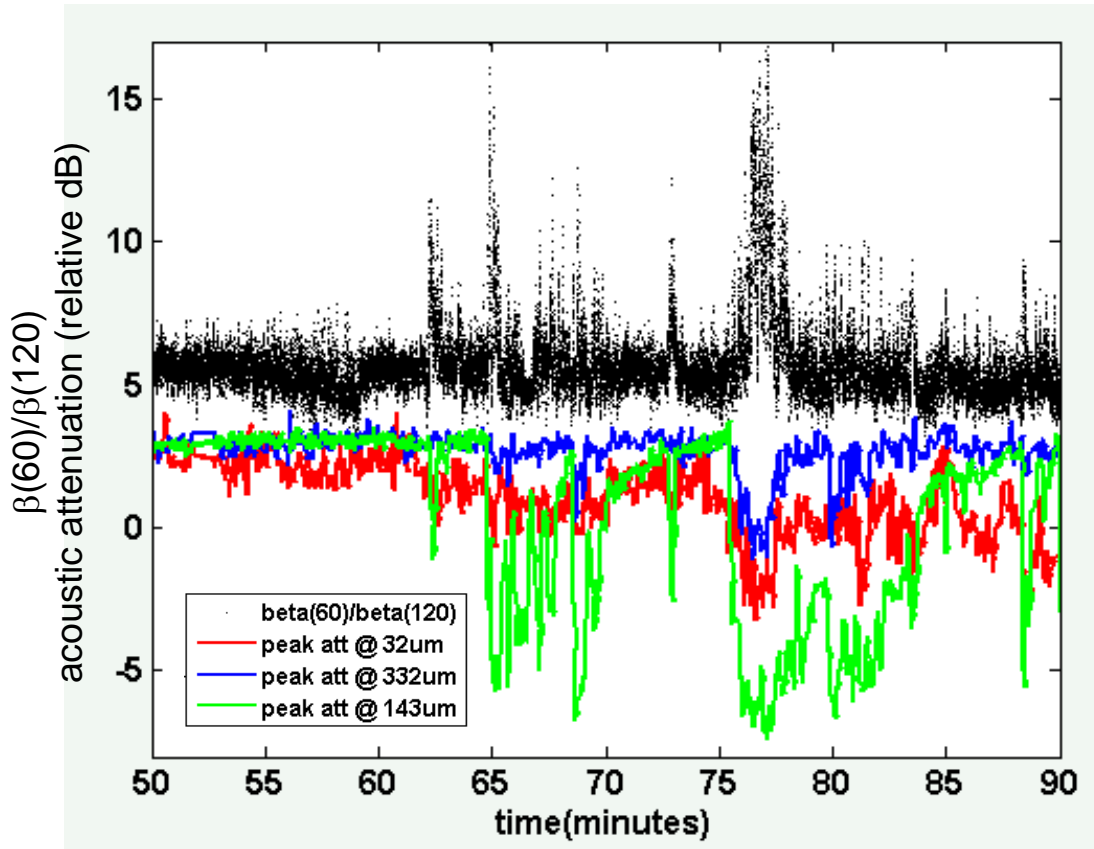


Figure 7. Patterns of relative acoustic attenuation from a bubble resonator were consistent with positive responses in $\beta(60)/\beta(120)$ from the MASCOT. The time series shown here is a subset of the data shown in Fig. 4. Bubbles, particularly those greater than 10 μ m, exhibit a marked enhancement in the volume scattering function in the mid-angles, thus $\beta(60)/\beta(120)$ increases. Note that the turbidity maximum observed around 59-60 minutes in Fig. 4 is associated with a decreasing $\beta(60)/\beta(120)$ and no acoustic response. This is consistent with the previous interpretation that this turbidity plume is dominated by sediments. A particularly close agreement was observed between $\beta(60)/\beta(120)$ and acoustic attenuation at the frequency specific for 143 μ m diameter bubbles. Note that even though the two sensors were on the same instrument package, sample volumes were separated by about 60 to 70 cm.

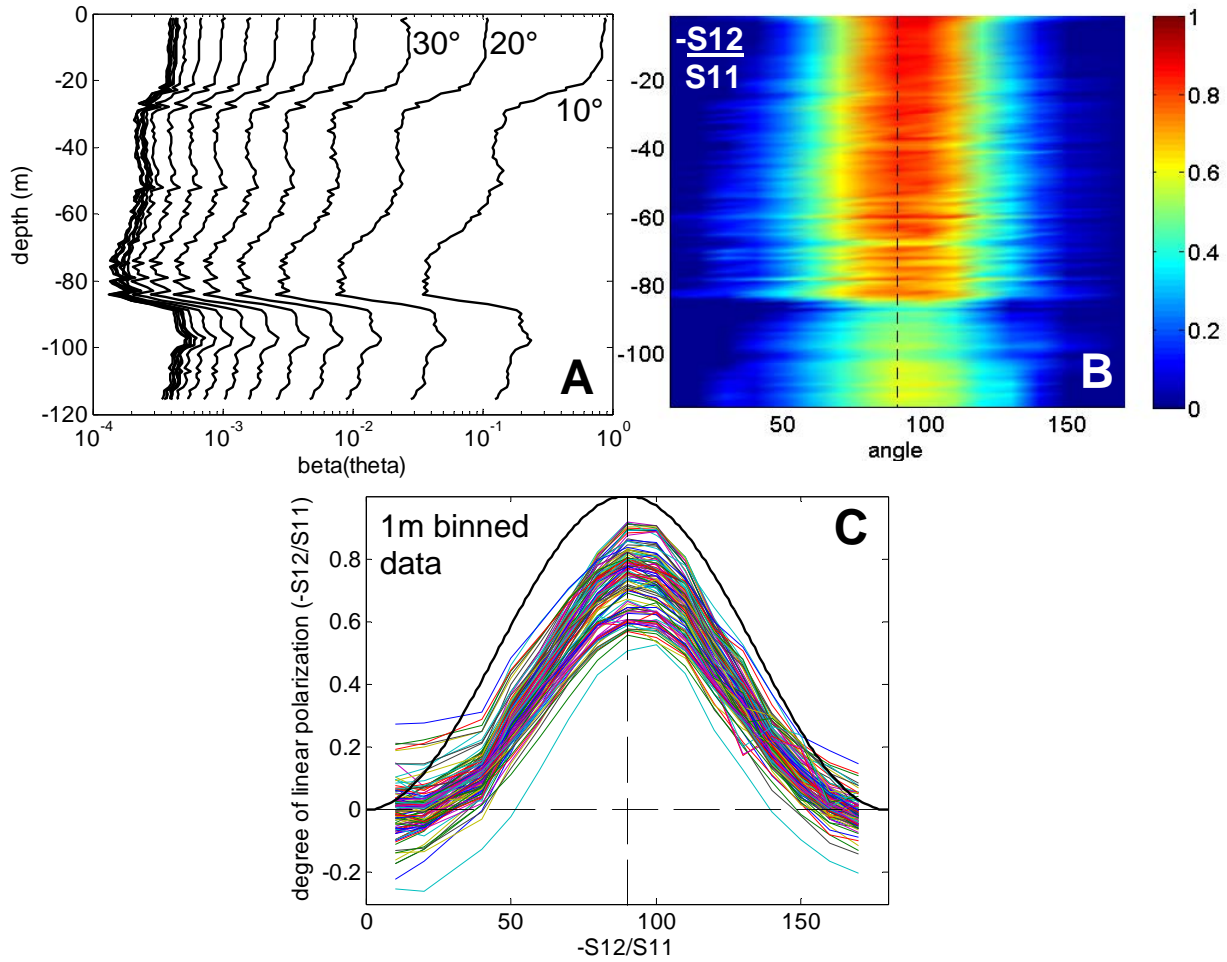


Figure 8. Vertical profile of volume scattering parameters collected in Santa Barbara Channel, September 2008. Volume scattering function resolved at 10 to 170 degrees at 10 degree increments as a function of depth exhibited maxima in the 20 m surface mixed layer and in a deep layer from 85 to 115 m (A). The clearest water was observed around 80 m. The linear degree of polarization ($-S_{12}/S_{11}$) as a function of depth and angle showed a maximum close to 0.9 at 90 degrees at the very surface, with a steady decrease with depth. The deep scattering maximum exhibited much lower polarization, as low as 0.5 around 85 m, likely indicative of greater bulk particle refractive index and increased bulk nonsphericity. All of the 1 m binned polarization functions are plotted as an overlay in panel C. The solid black curve in panel C passing through zero at 0 and 180 degrees and 1 at 90 degrees is the Rayleigh ideal. The maximum in polarization is shifted slight to the larger angle side of 90 degrees. All these observations are consistent with the few previous measurements made by Voss and Fry (1984) and Quinby and Hunt (1988). This is the first time these measurements have been made in-situ in an undisturbed remote volume.

IMPACT/APPLICATIONS

Progress and results represent important steps toward the development of a multi-angle, in-water VSF device. Knowledge of the Inherent Optical Properties including the VSF can be used to predict and optimize the performance of a host of Naval operations that rely on divers, cameras, laser imaging systems, and active and passive remote sensing systems. These include mine countermeasures, harbor security operations, debris field mapping, anti-submarine warfare, and search and salvage operations. These measurements may also be used in environmental monitoring and research applications for determining particle composition.

TRANSITIONS

We expect that our efforts in developing an in-water VSF device and associated inversion techniques to better understand particle dynamics in natural waters will lead to transition as operational tools for the fleet and the oceanographic research community in the future.

RELATED PROJECTS

This effort is related to several ongoing efforts to develop optical sensors and associated biogeochemical inversion techniques. Related projects include:

- resolving the optics and dynamics of subsurface bubble populations in the S. Ocean,
- developing improved vicarious calibration and validation methods for ocean color satellite remote sensing,
- investigating the sources of backscattering in natural waters,
- developing tools for ocean observing systems, and
- developing a surfzone optical mine countermeasure drifter.

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PATENTS

Scattering attenuation meter (SAM), pending.

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